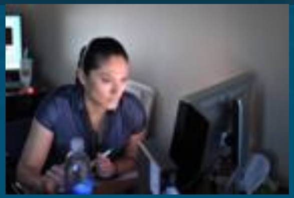
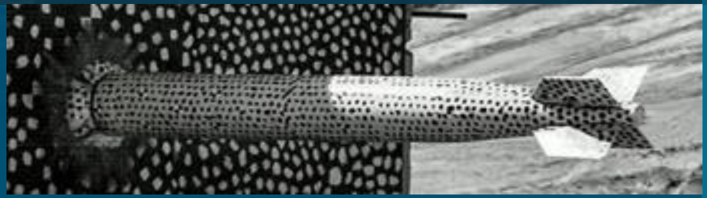
Developing a Benchmark Evaluation from the Experiments Performed on the Space Nuclear Thermal Propulsion Zero-Power Critical Assembly (SNTP-CX)





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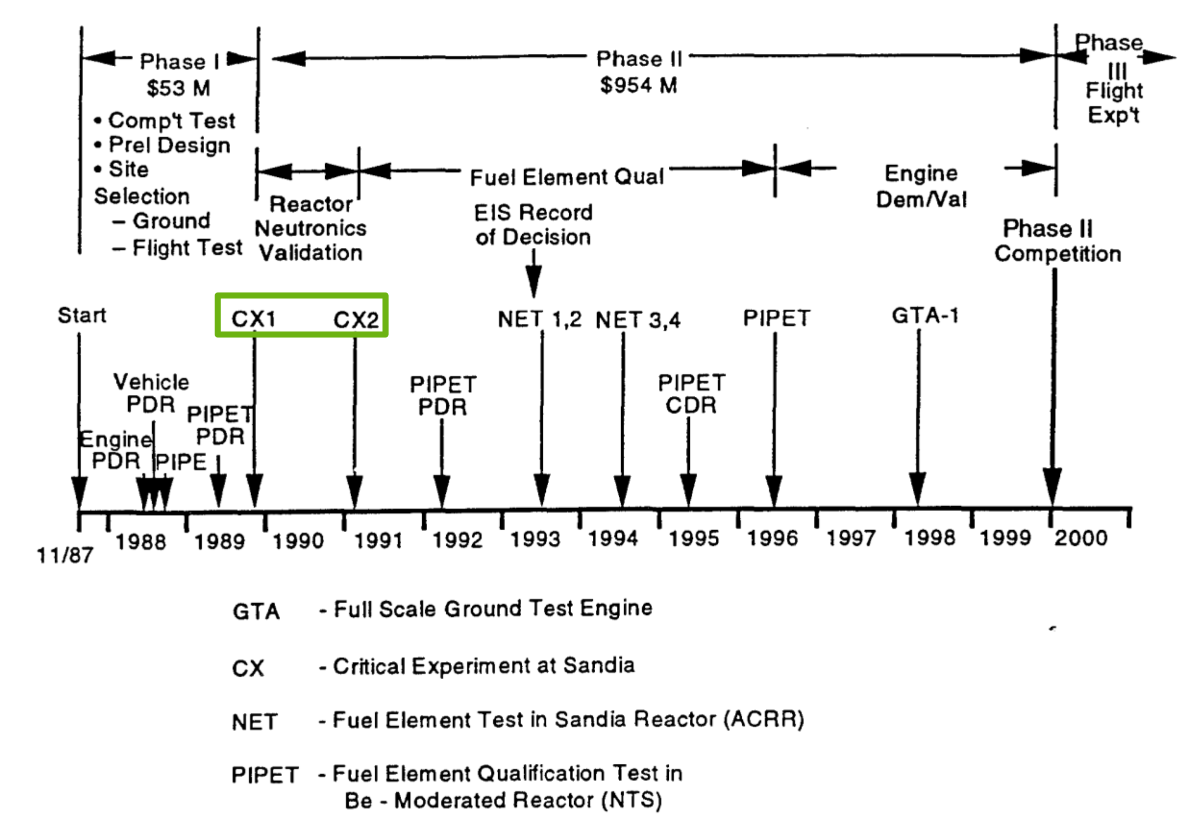
The SNTP Program: 1987-1994

Purpose: To develop a new rocket capable of twice the performance of a standard chemical rocket using nuclear technologies.

Designed as Three Phase Effort

- Phase I: Proof of concept of particle bed reactor engine.
- Phase II: Perform ground test of the particle bed reactor engine.
- Phase III: Perform flight test of the particle bed reactor engine.
- Program terminated in 1994 before phase III began.



[1]

SNTP-CX

Decided a zero power critical assembly was needed

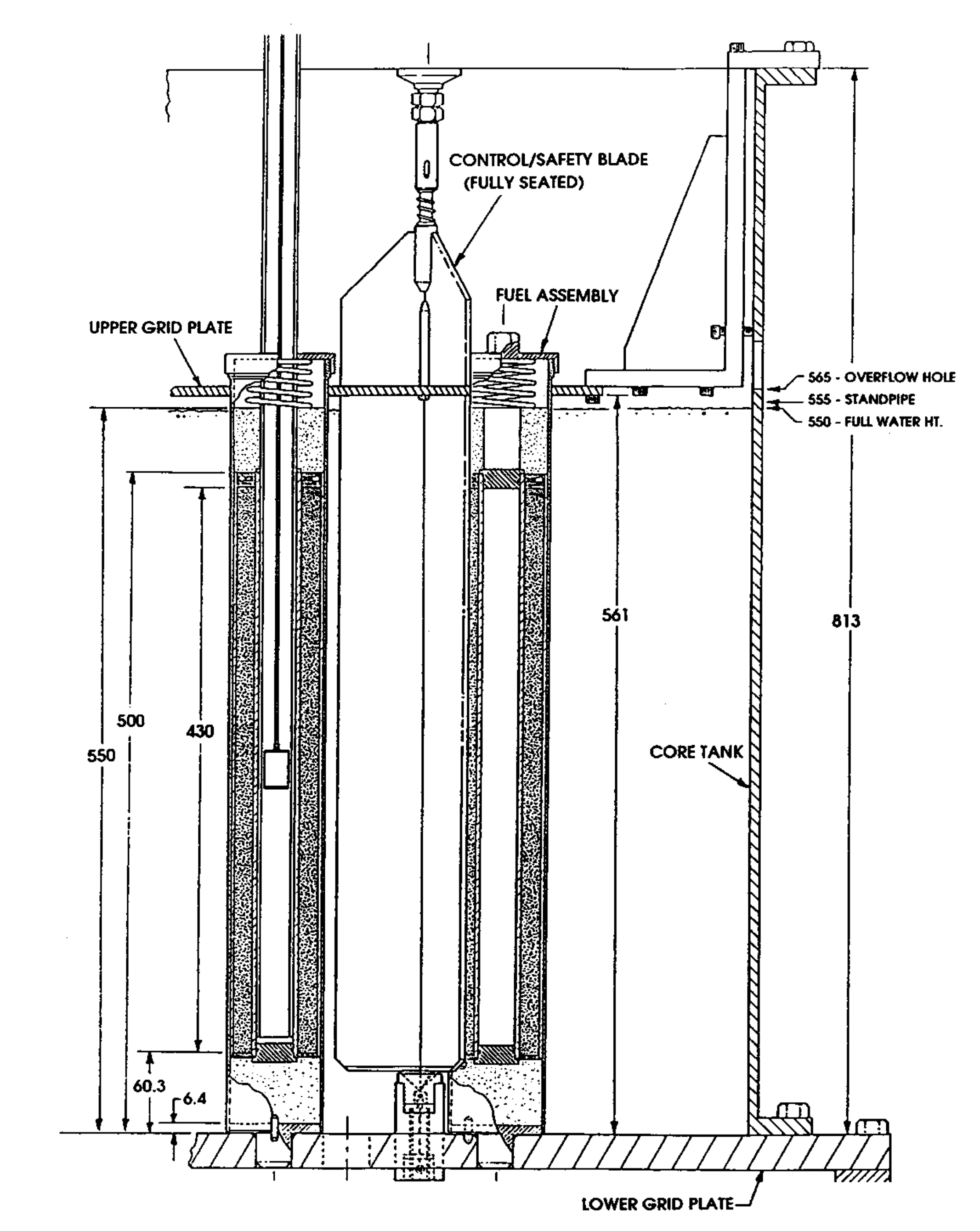
Designed by SNL and B&W

Installed and operated at SNL

142 runs performed for various experiments from 1989 to 1992

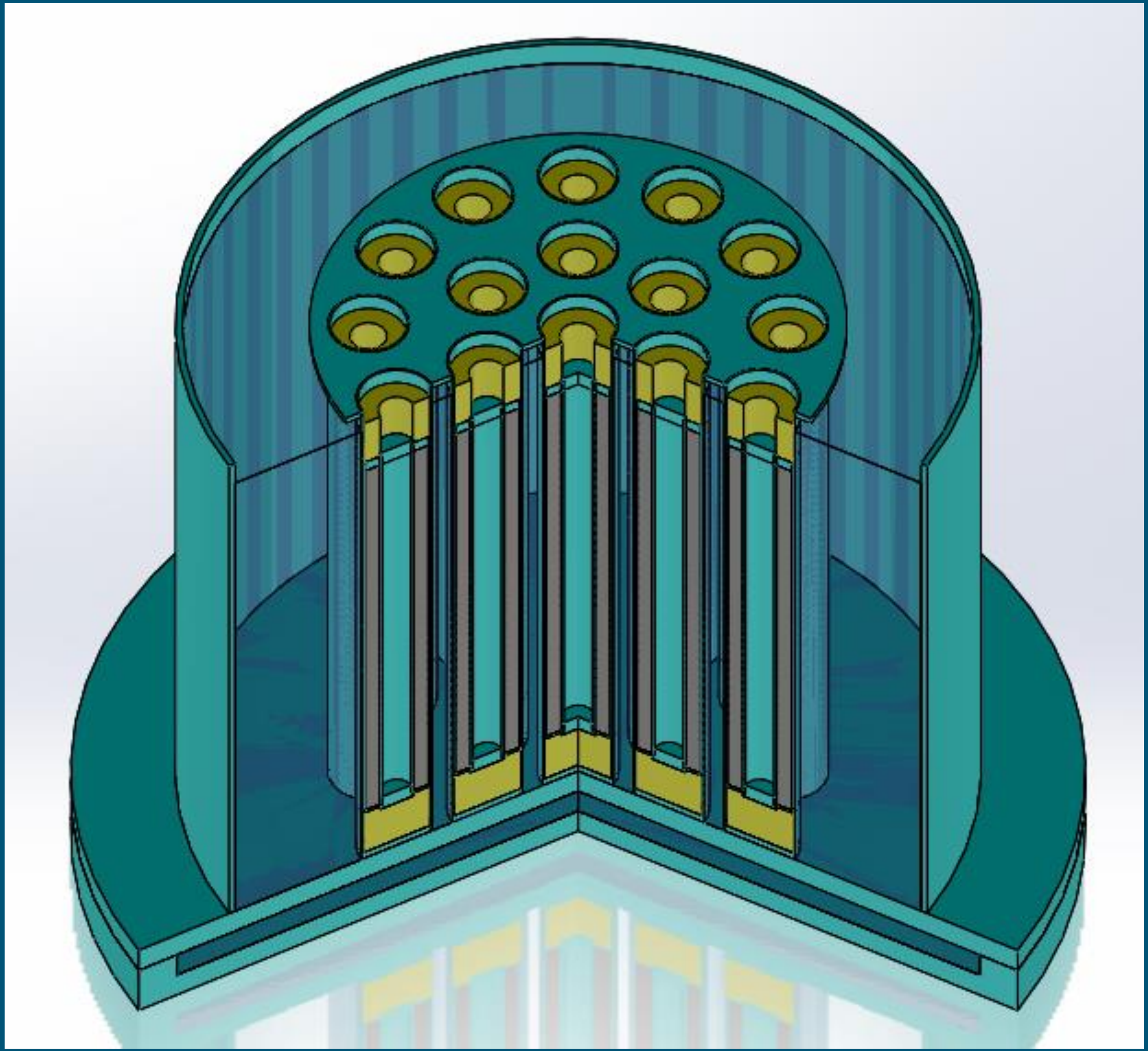
19 fuel stalks on a 9.4 cm triangular pitch

Fuel annulus is a multi-particle type packed bed



[2]

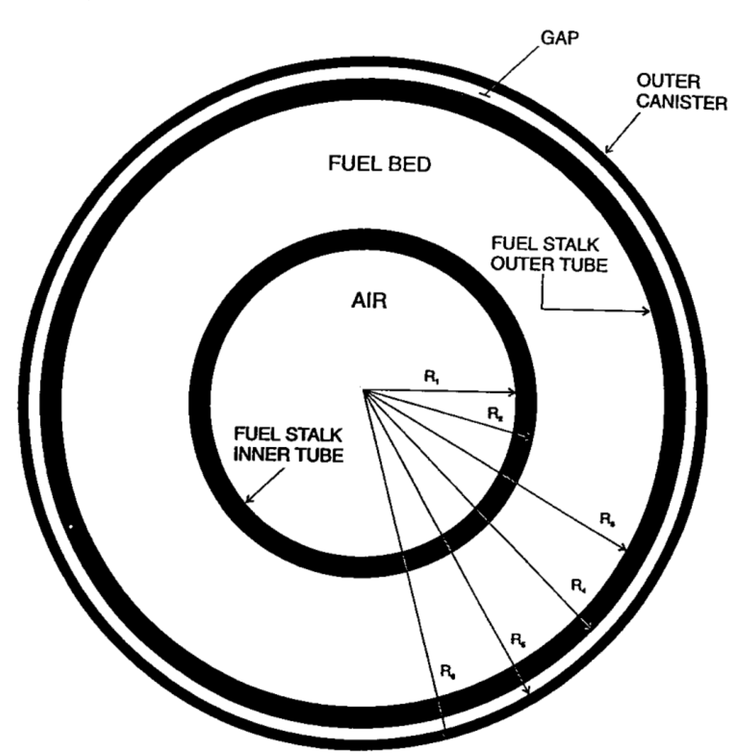
SNTP-CX



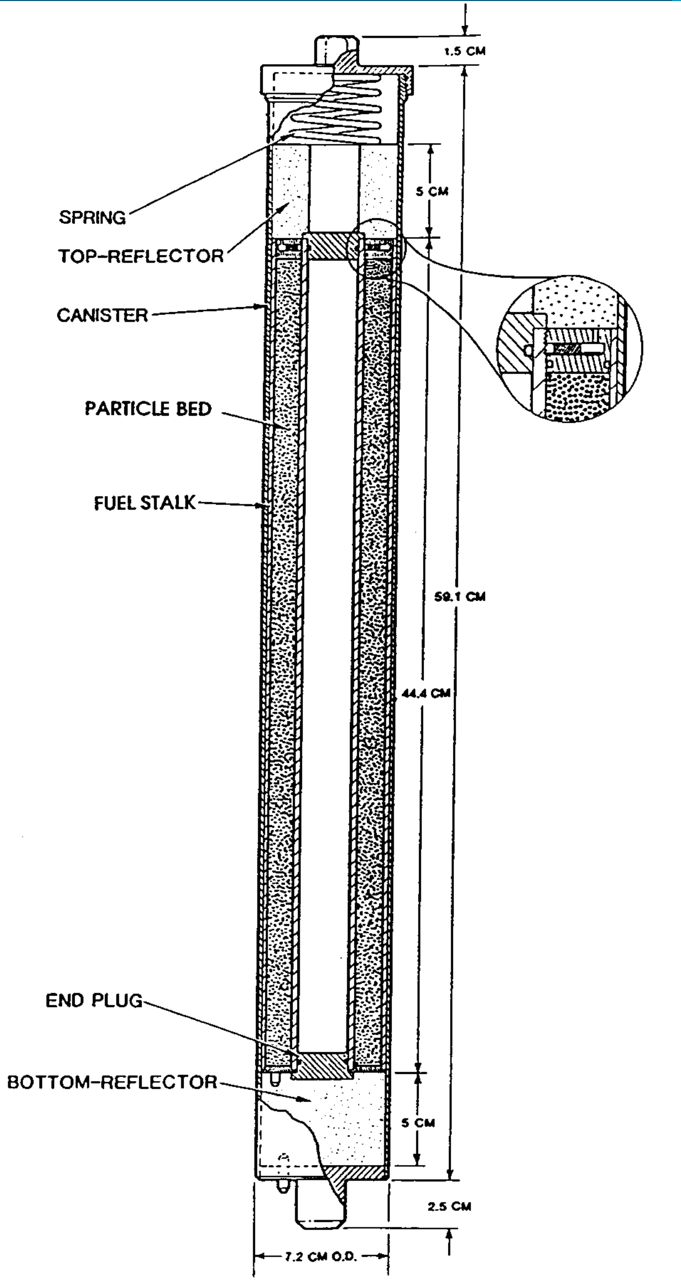
The Particle Bed

3 Particle Types

- Fuel particle
  - UC kernel (93 w/o U-235 nominal enrichment)
  - Carbon graphite shell
- Carbon particle
  - Versar CARBOSPHERE Type S220
  - 6.2 w/o Sulfur impurity
- Zircaloy-4 particle



Dimension	Design (mm)	As-Built Average (mm)
2 X R_1	29.44±0.13	29.39
2 X R_2	35.43±0.13	35.48[1]
2 X R_3	66.12±0.13	66.09
2 X R_4	69.27±0.23	69.24
2 X R_5	69.54±0.13	69.72
2 X R_6	72.69±0.23	72.82



Particle Bed Information

What we have

- Particle bulk densities
- Material compositions
- Total particle mass loaded/stalk
- Particle size
- Packing fraction of 0.64 [3]

Particle	Bulk Density (g/cc) [2]	Diameter (µm) [3]	Uncertainty (µm) [3]
Fuel Kernel	5.47	275	±25
Carbon Shell (Thickness)*	-	15	±5
Zircaloy-4	4.256	231	±19
Carbon	1.269	231	±19

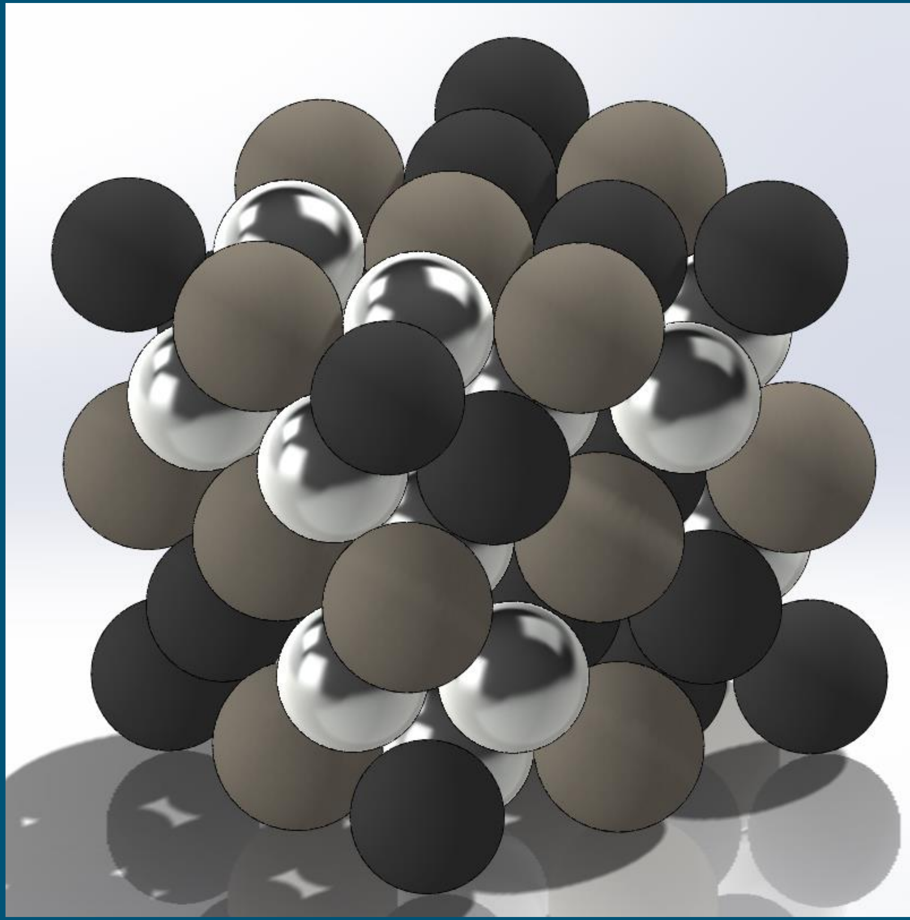
Stalk ID	Particle Masses, Grams		
	Fuel (g)	Zircaloy-4 (g)	Carbon (g)
S890427	1410.100	1791.100	474.500
S890530	1402.300	1821.700	472.100
S890606	1397.500	1784.100	477.500
S890621	1331.300	1787.200	490.300
S890622	1411.600	1760.000	482.770
S890706(a)	1441.400	1740.200	476.500
S890706(b)	1358.100	1788.400	484.750
S890711(a)	1442.500	1773.500	464.800
S890711(b)	1349.100	1794.600	479.200
S890714	1331.450	1808.800	480.500
S890717	1434.500	1762.150	468.920
S890718	1417.300	1785.700	469.600
S890721	1407.900	1794.300	471.600
S890728(a)	1355.100	1794.200	472.400
S890808(a)	1379.020	1785.300	480.800
S890808(b)	1382.060	1825.050	468.470
S890808(c)	1387.210	1774.890	477.210
S890814	1347.920	1802.810	476.710
S890816	1365.460	1777.570	478.140
AVG	1386.938	1786.925	476.146
STD DEV	34.558	19.903	6.122
STD DEV/AVG	0.025	0.011	0.013

[2]

General Approach to Modeling

Dark Grey = Carbon Particle
Light Grey = Fuel Particle
Silver = Zircaloy-4 Particle

1. Estimate particle fractions
2. Choose lattice type and size
   - Size referring to number of particles per lattice element
3. Ensure total masses are correct by:
   - Using iterative process to:
     - Adjust Carbon and Zircaloy-4 particle radii
     - Adjust $UC_{1.7}$ kernel and C shell material densities



Estimating Particle Fractions

Assumptions

- Particles were of nominal radii
- Material densities were all equal to the bulk density/packing fraction

Calculate mass of each particle type

Divide total mass by particle mass

Particle	Estimated # of Particles	Particle Fraction
Fuel	1.41E+07	0.185
ZR-4	3.28E+07	0.430
C	2.94E+07	0.385
Totals	7.63E+07	1.000

Choosing a lattice type

Desirable traits

Packing fraction of at least 0.64

High particles/unit cell

- Allows to get closer to estimated particle fractions

Lower modeling difficulty preferred

Face Centered Cubic (FCC)

Max packing fraction of 0.72

4 particles per unit cell

Easily expandable

- Allows for more particles per lattice cell
- 1 lattice cell = 2x2x2 unit cells = 32 total particles
  - 6 fuel, 12 carbon, 14 zircaloy-4

Easily modeled

- MCNP square lattice (type 1)
- Particle positions in the lattice cell can be defined as a function of side length

Lattice Side Length, Particle Sizes and Material Densities

Iterative process choosing values to ensure total stalk mass for each particle type is conserved.

Initial conditions

- 6 Fuel, 12 Carbon, 14 Zircaloy-4
- UC kernel radius = 125 μm
- C shell thickness = 15 μm
- Carbon density = bulk density/packing fraction = 1.269/0.64 = 1.983 g/cc
- Zircaloy-4 density = bulk density/packing fraction = 4.256/0.64 = 6.650 g/cc

Iterated values

- UC kernel and C shell density
- Carbon and Zircaloy-4 particle radius
- Lattice cell side length

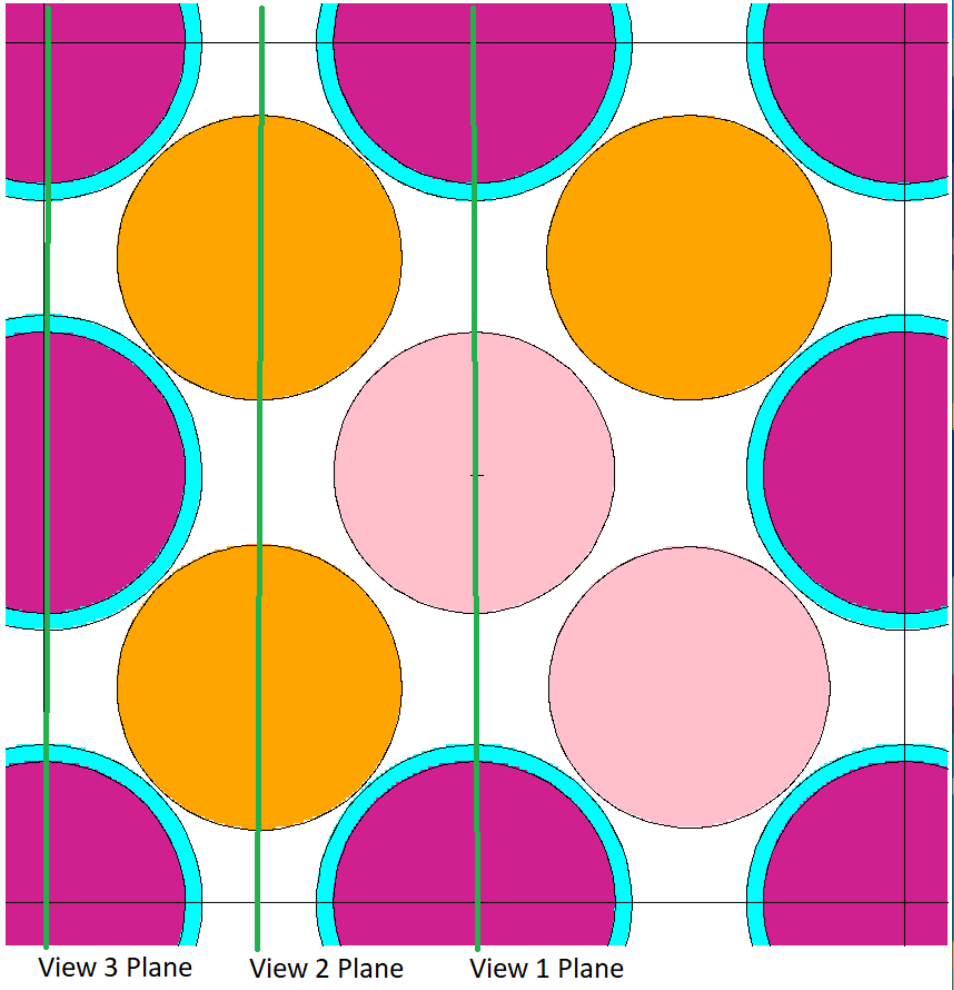
Final Lattice

Lattice side length = 762.7583 μm

Fuel particle lattice positions fixed

Filler particle lattice positions randomized

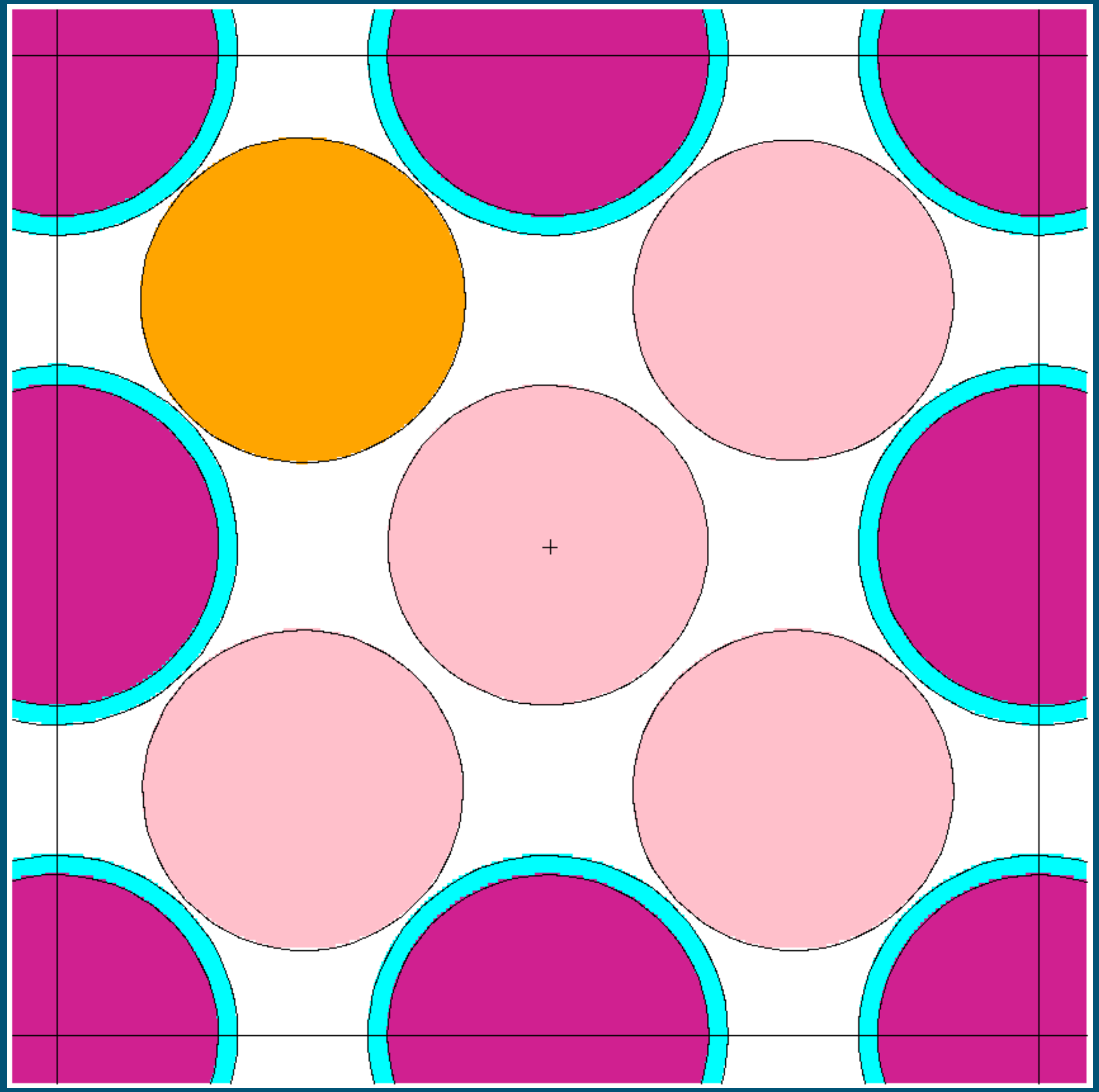
Purple/Blue = Fuel Particle
Orange = Carbon Particle
Pink = Zircaloy-4 Particle



Particle	# per lattice element	thickness/ radius (μm)	density (g/cc)	Stalk Mass Delta (g)
Fuel Kernel	6	125	11.201	9.90E-03
Fuel Shell	-	15	1.827	-4.15E-05
Carbon	12	126.4	1.983	-8.61E-04
Zircaloy-4	14	124.6	6.650	1.34E-04

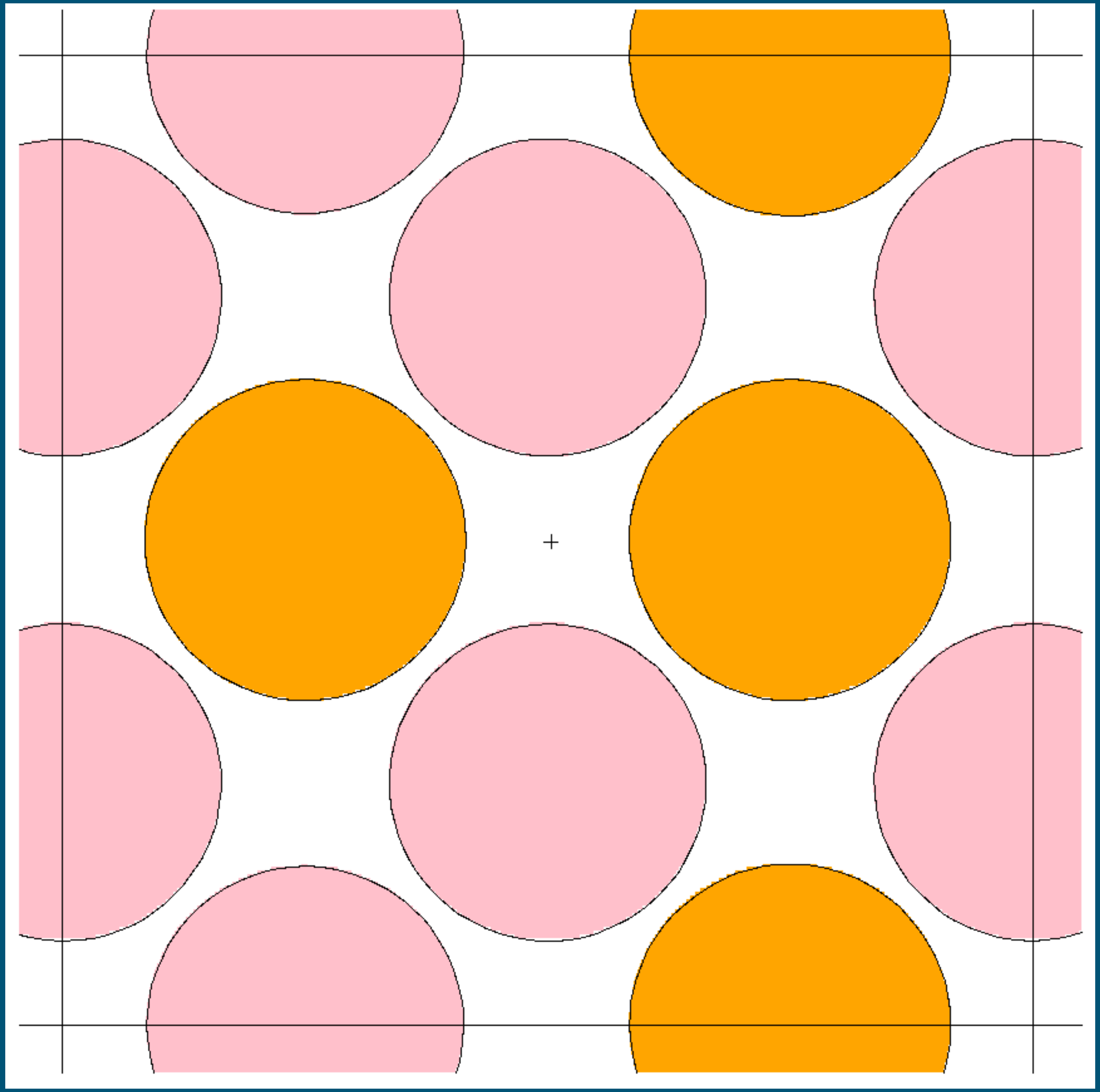
View 1:YZ – Center Plane

Purple/Blue = Fuel Particle
Orange = Carbon Particle
Pink = Zircaloy-4 Particle



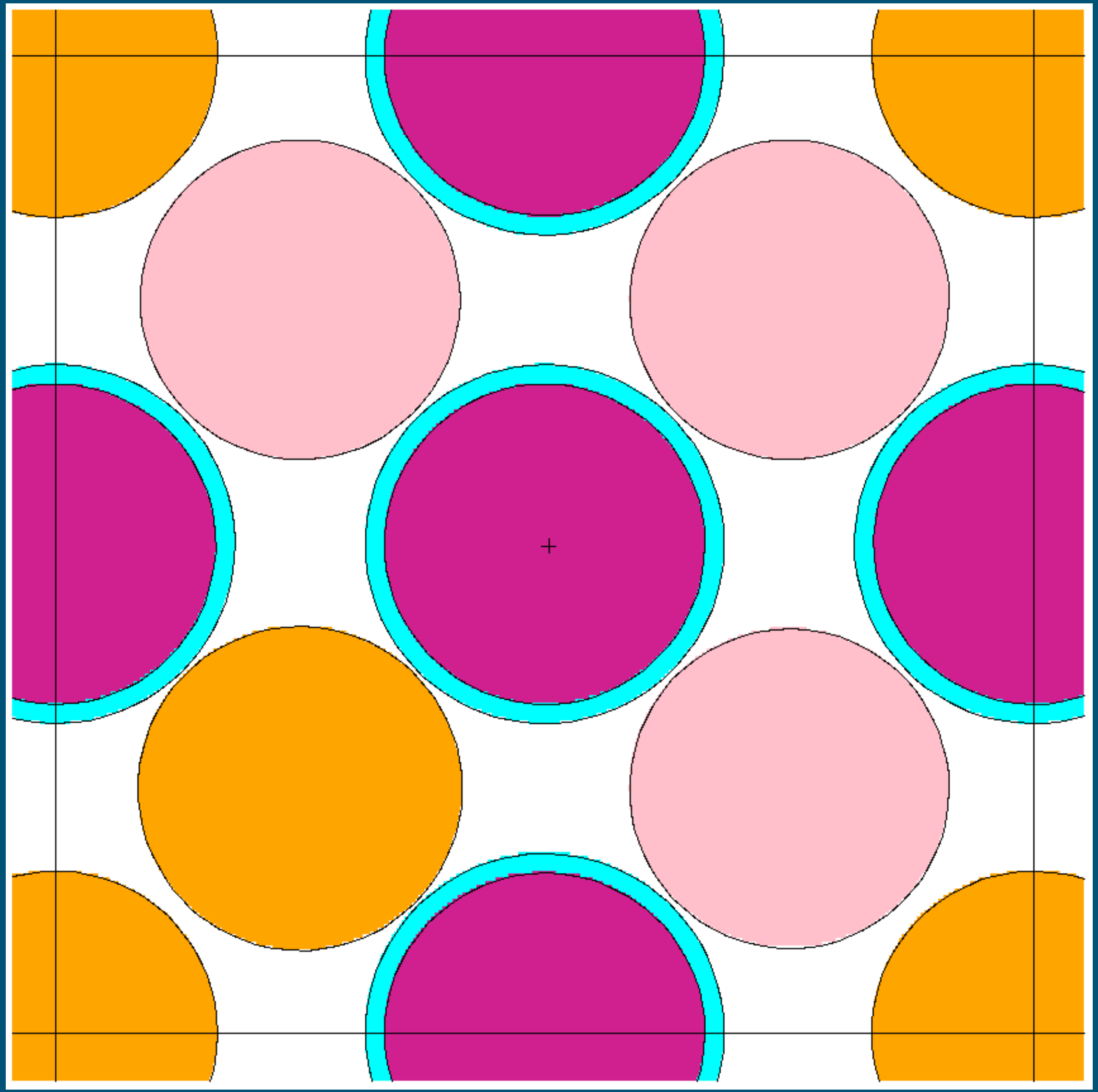
View 2: YZ – Mid Plane

Purple/Blue = Fuel Particle
Orange = Carbon Particle
Pink = Zircaloy-4 Particle

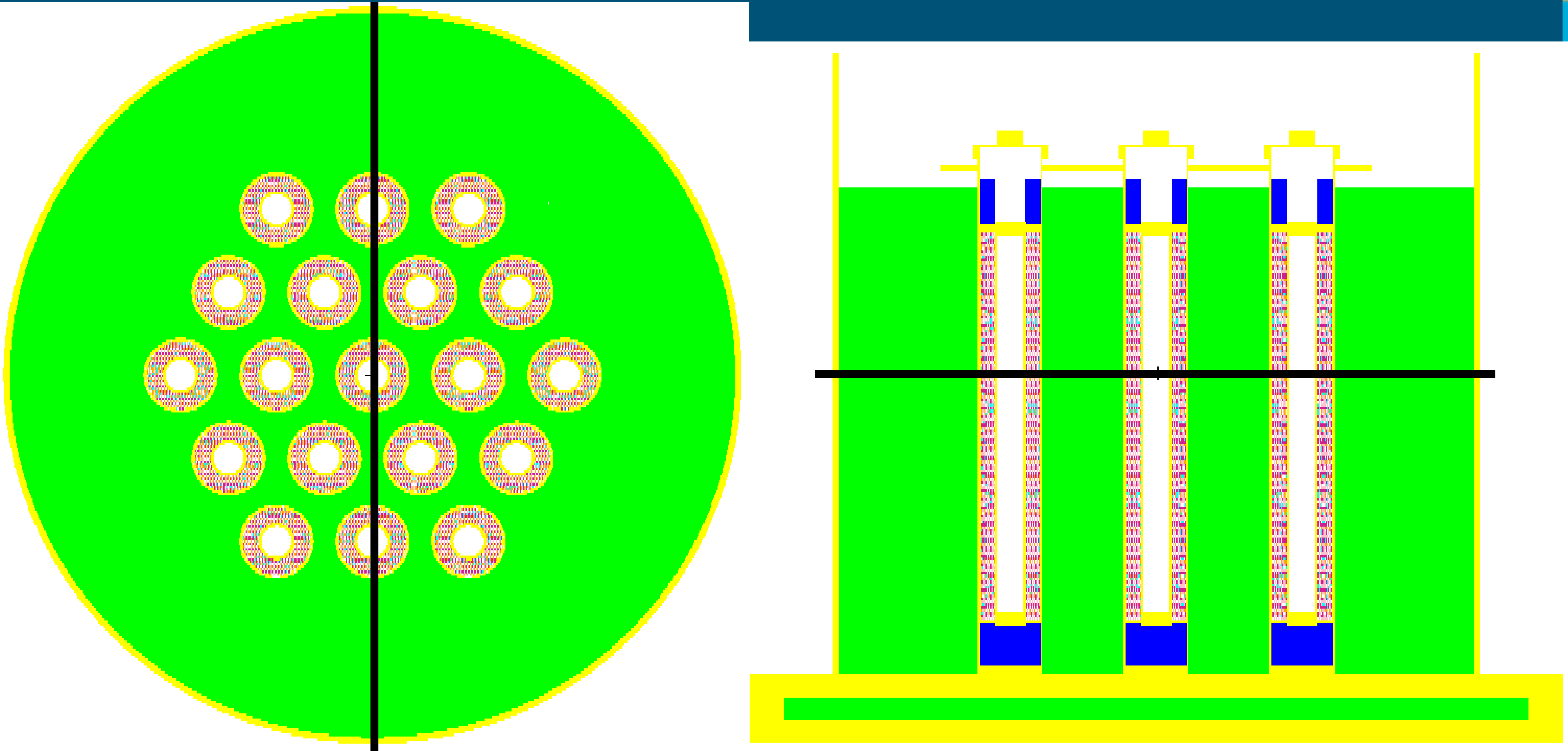


View 3: YZ – Face Plane

Purple/Blue = Fuel Particle
Orange = Carbon Particle
Pink = Zircaloy-4 Particle



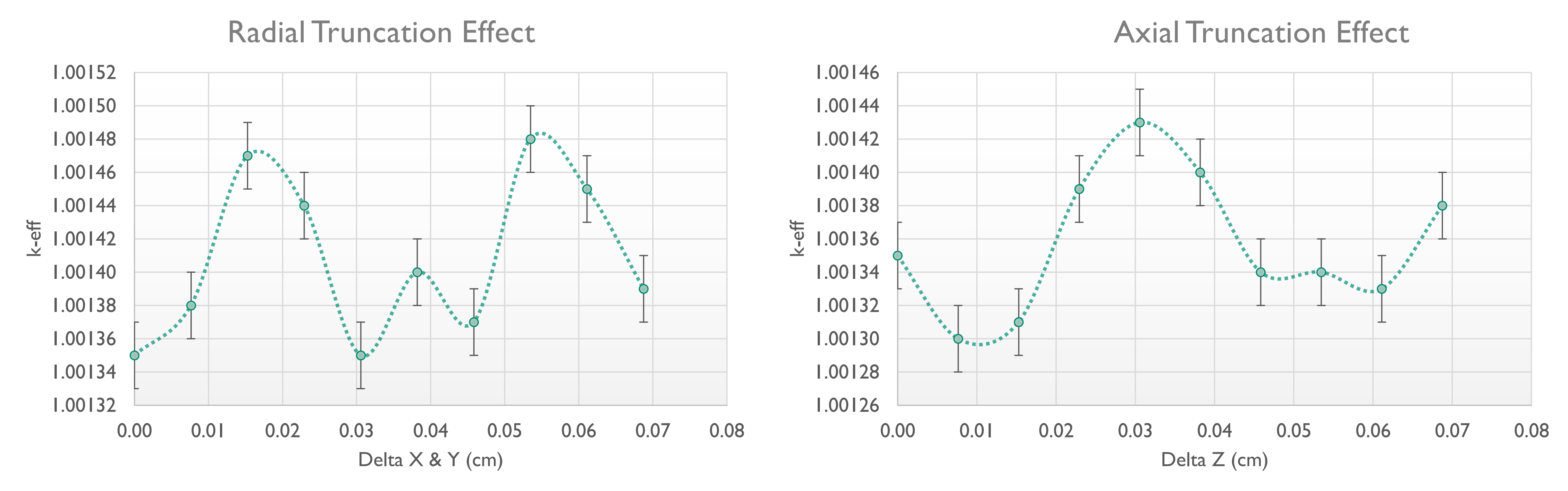
MCNP Model Views



Particle Boundary Truncation Analysis

The effects of the particle truncation at the fuel annulus boundaries were looked at.

- Tested in both radial and axial directions
- Particle bed shifted in increments of 1/10 the lattice cell side length
- No correlation made



Base Model Results

Model is representative of a critical experiment (k_{eff} = 1.0)

- Using case 1 critical parameters

Discrete particle modeling brings model closer to critical

Utilizing the "average stalk" results in slightly lower reactivity

Model	k-eff	std. dev.
Individual Detailed	1.00151	0.00005
Average Detailed	1.00141	0.00004
Individual Smeared	1.00319	0.00004
Average Smeared	1.00293	0.00005

Boron Worth Experiments

Experiment series was conducted to measure the boron reactivity worth in the moderator.

- 10 different boron concentrations tested
- Moderator height used as approach to critical parameter
- Control and safety blades fully withdrawn
- 19 runs performed
  - 10 Critical water height measurements (yellow)
  - 9 Reactivity measurements at the previous boron concentrations critical water height (blue)

Case	B PPM	Water Height (mm)	Reactivity (Cents)	B Worth (Cents/ PPM)
1	68.89	NA	NA	NA
		542.5	0	
2	61.66	542.5	18.26	-2.52559
		534.6	0	
3	55.12	534.5	17.7	-2.70642
		528.4	0	
4	47.71	528.4	20.16	-2.72065
		522.2	0	
5	39.86	522.2	22.63	-2.88280
		516.2	0	
6	32.7	516.2	22.56	-3.15084
		510.7	0	
7	24.21	510.7	22.76	-2.68080
		505.2	0	
8	16.54	505.2	21.98	-2.86571
		500.1	0	
9	8.69	500.1	26.1	-3.32484
		494.5	0	
10	0.27	494.5	30	-3.56295
		488.4	0	

[2]

Modeling the Boron Worth Experiments

- Model created using methods described above
- 19 models are identical varying only in boron concentration and water height
- Boron worth calculated form the model is within 1 standard deviation of the experimentally measured values
- Model is behaving as expected

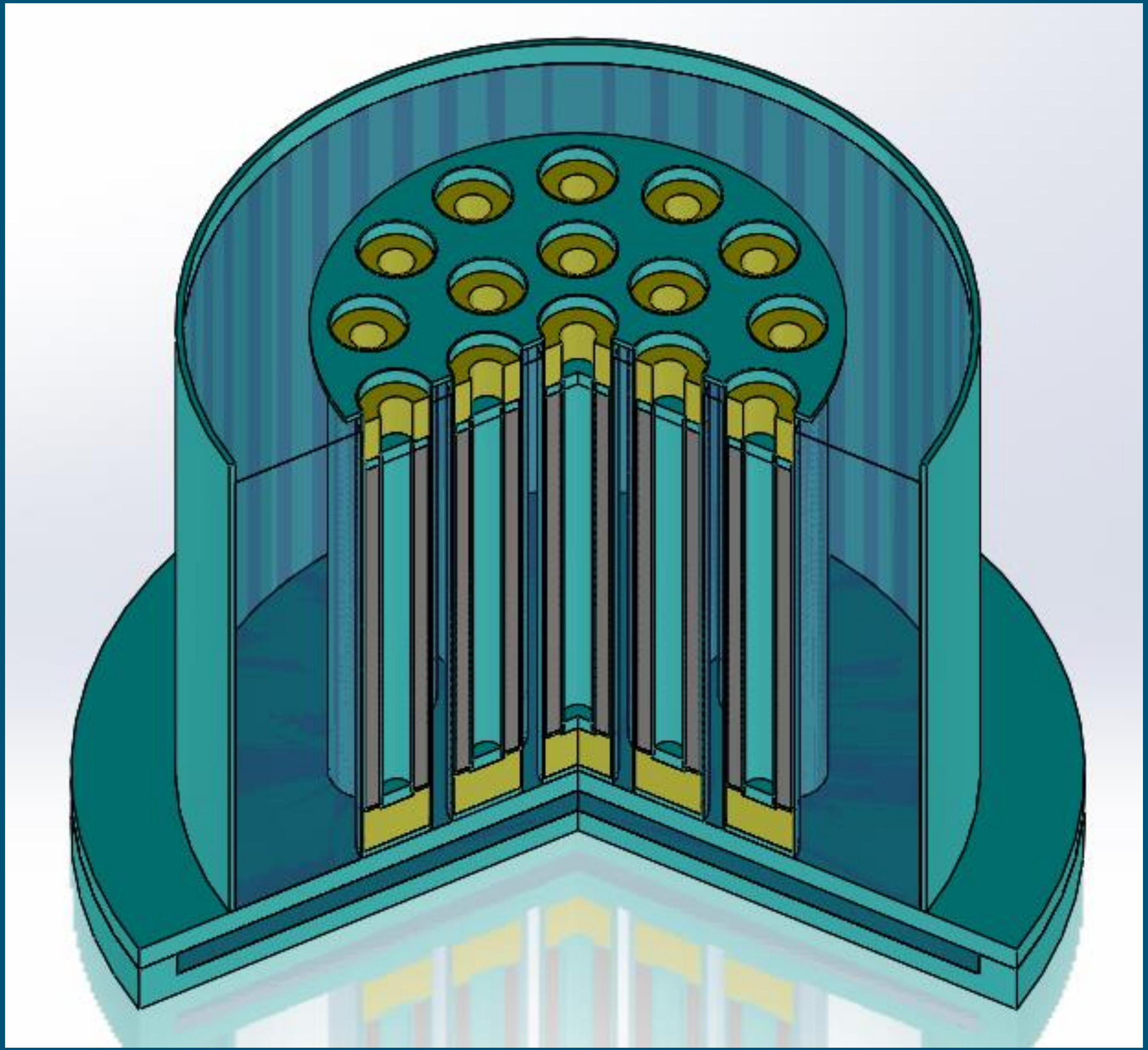
Case	B PPM	Water Height (mm)	Reactivity (Cents)	B Worth (Cents/ PPM)	Std. Dev. (Cents)
1	68.89	NA	NA	NA	NA
		542.5	23.19574		
2	61.66	542.5	43.14874	-3.30471	0.81411
		534.6	28.40898		
3	55.12	534.5	44.54397	-3.20497	0.89826
		528.4	31.47394		
4	47.71	528.4	51.38881	-3.40904	0.71808
		522.2	34.84398		
5	39.86	522.2	55.18832	-3.34560	0.71771
		516.2	37.44709		
6	32.7	516.2	53.92207	-3.18935	0.71766
		510.7	35.30342		
7	24.21	510.7	57.97319	-3.37649	0.71753
		505.2	38.05946		
8	16.54	505.2	57.59351	-3.38968	0.71742
		500.1	39.13099		
9	8.69	500.1	58.73249	-3.34373	0.71731
		494.5	36.06908		
10	0.27	494.5	60.37732	-3.61460	0.81242
		488.4	31.93358		

Future Work

- Determine causes for consistently increased multiplication factor in the model compared to the experiments
- Continue to close information gap
- Complete uncertainty analysis
- Finalize simplified model

<u>Acknowledgements</u>

The work presented here is supported by the DOE Nuclear Criticality Safety Program (NCSP), funded and managed by the National Nuclear Security Administration for the Department of Energy



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